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Recent MIT Research on Residual Stresses and Distortion in Welded Structures

IVB-3

Koichi Masabuchi, Member, Massachusetts Institute of Technology

ABSTRACT

This paper presents a summary ofrecent efforts by the Welding Research Group at the Department of Ocean Engineering, M.I.T. The major thrust of the efforts has been to develop technologies of reducing residual stresses and distortion through in-process ‘control. Part I discusses (a) reduction of longitudinal bending distortion of built-up beams, (b) reduction of radial distortion and residual stresses in girth-welded pipes, (c) reduction of forces acting on tack welds during butt welding, and (d) reduction of residual stresses and distortion in high-strength steel weldments. Part II presents a brief summary of other studies including (e) forming of steel plates by line heating with a high-power laser beam, (f) an intelligent system for flame straightening of panel structures, and (g) a knowledge-based system for minimizing out-of-plane distortion of welded panel structures.

INTRODUCTION

Residual stresses and distortion are major problems associated with welding fabrication of large, complex structures including ships, submarines, and offshore structures. Because a weldment is locally heated by the welding heat source, complex thermal stresses occur during welding, and residual stresses and distortion remain after welding is completed. These stresses and distortion have various consequences, most of which are detrimental to the integrity of welded structures. Correcting unacceptable distortion is very expensive and in some cases impossible. Engineers in the shipbuilding industry will face severer problems with residual stresses and distortion in the years ahead, because:

(a) We are using increasing amounts of thinner sections which tend to distort more,
(b) We are using increasing amounts of aluminum alloys and other non-ferrous alloys which tend to cause more distortion problems,
(c) Some structures such as deep diving submarines must be fabricated with increasingly more stringent tolerance for distortion, especially out-of-plane distortion.

The author believes that the best way of dealing with these problems is to develop technologies for controlling and reducing residual stresses and distortion during fabrication. The best method of accomplishing this is to utilize real-time controls during welding while non-elastic strains that cause these stresses and strains are being formed.

The Welding Research Group at the Department of Ocean Engineering of the Massachusetts Institute of Technology has (for many years) performed research on various subjects related to residual stresses and distortion in welded structures. The major thrust of recent research efforts has been to advance the state-of-the-art of controlling and reducing residual stresses and distortion in weldments. Additional studies with other objectives also have been performed. This paper reviews these efforts in the following two parts:

Part 1: In-process reduction and control of residual stresses and distortion in weldments

Part 2: Summary of other research activities.

PART 1: IN-PROCESS REDUCTION AND CONTROL OF RESIDUAL STRESSES AND DISTORTION IN WELDMENTS

Basic Concept of In-Process Control of Residual Stresses and Distortion

The reason why real-time control is important for reducing residual stresses and distortion can be understood by studying mechanisms of their formation. Figure 1 shows schematically how a rectangular plate deforms when arc welding is performed along its upper longitudinal edge.

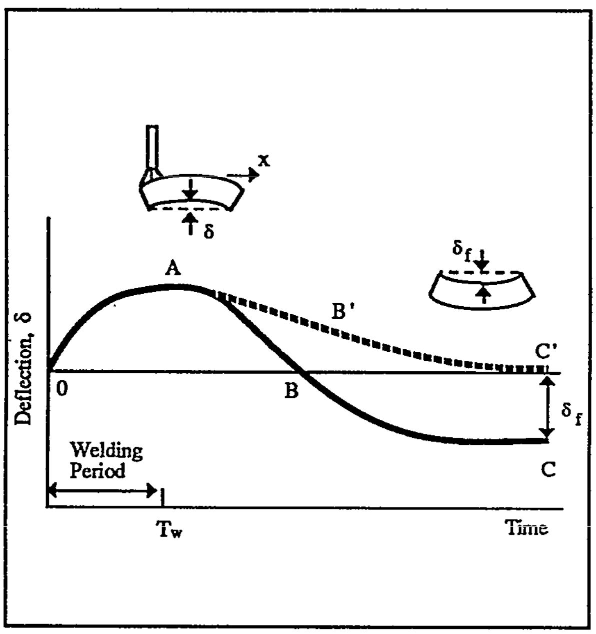


Figure 1 Transient Deformation of a Rectangular Plate During and After Welding

Since temperatures are higher in regions near the upper edge, these regions expand more than regions near the lower edge causing the upward movement of the center of the plate, δ,, as shown by Curve OA. The most important stress component is the longitudinal stress, ox. Stresses in regions near the weld are compressive, because thermal expansions in these regions are restrained by the surrounding metals at lower temperatures. Since the temperatures of the regions near the weld are quite high and yield stresses of the material are low, compressive plastic strains are produced in these regions. When welding is completed and the plate starts to cool, it deforms in the opposite direction. If the material was completely elastic during the entire period of the heating and cooling cycle, the plate would deform as shown by Curve OAB'C' returning to its initial shape with no residual distortion. However, this does not happen during welding a real material, be it steel, aluminum, or titanium. As a result of the compressive plastic strains produced in regions near the upper edge, the plate continues to deform after passing its initial shape, as shown by Curve OABC, resulting in the negative final distortion, δ_f f, when the plate cools down to its initial temperature.

The most effective way of reducing distortion is to control the formation of plastic strains produced in regions near the weld. The difficulty here is that the necessary control must be maintained during welding while the weldment undergoes complex changes of thermal stresses. In order to have correct and consistent controls, one must have the following capabilities:

(1) <u>Prediction capability.</u> One must have a proper capability of predicting, by analysis, prior experiments, and/or experience, (a) how the weldment being studied deforms and (b) how to perform proper controls to change the distortion being considered.

(2) Sensing capability. One must also have a proper device or devices for sensing if what should happen is actually happening.

(3) Control capability. If one finds that what is actually happening is different from what is suppose to happen, it is important that he/she has capability of making necessary changes, in real-time if needed.

Efforts have been made to improve these capabilities.

Regarding prediction capability, a series of computer programs have been developed including (a) simple one-dimensional programs which analyze only the stress component parallel to the weld line or the longitudinal stress and (b) finite-element programs capable of analyzing more complex stress fields [1]. Although the one-dimensional programs can analyze only the longitudinal stress, they are fast and very economical to use. On the other hand, finite element programs are capable of analyzing stresses in more complex fields, but they tend to be slow and expensive to operate.

Regarding sensing capability, efforts have been made for improving techniques for measuring out-of-plane distortion. The following systems have been developed and used [2]:

(a) A laser interferometer capable of non-contact measurement of a minute amount of distortion by using a bright-and-dark grid system generated in space by a light system produced by a low-power laser beam;

(b) A laser vision system capable of non-contact measurement of relatively large amount of distortion by accurately measuring distances between the lower-powered laser source and measuring points; and

(c) A mechanical system nicknamed "octopus" capable of measuring radii of curvature in four directions around a measuring point by use of eight dial gages located along a circle surrounding the measuring point.

Regarding control capability, techniques involving alteration of heating patterns and application of additional forces were tried. Although uses of these techniques for controlling residual stresses and distortion in weldments have been tried for a number of years by many investigators, approaches taken in the past were primarily empirical or trial-and-error. The unique feature of the current effort. is the combination of control capabilities with prediction and sensing capabilities so that the effort becomes science rather than art.

The author recognizes that addition of other controls, either by changing thermal patterns and/or providing additional forces during manual welding, is unrealistic if not impossible. However, it should be possible to apply additional controls during automatic welding. In fact, it should be possible to develop a fixture that can apply needed controls during welding. Such a fixture may be called an "intelligent fixture."

Various studies have been done in the area of in-process control of residual stresses and distortion using prediction, sensing and control capabilities described above. Following are the subject areas of four of these studies.

Study 1: Reduction of longitudinal bending distortion of built-up beams,

Study 2: Reduction of radial distortion and residual stresses in girth-welded pipes,

Study 3: Reduction of forces acting on tack welds in a butt joint,

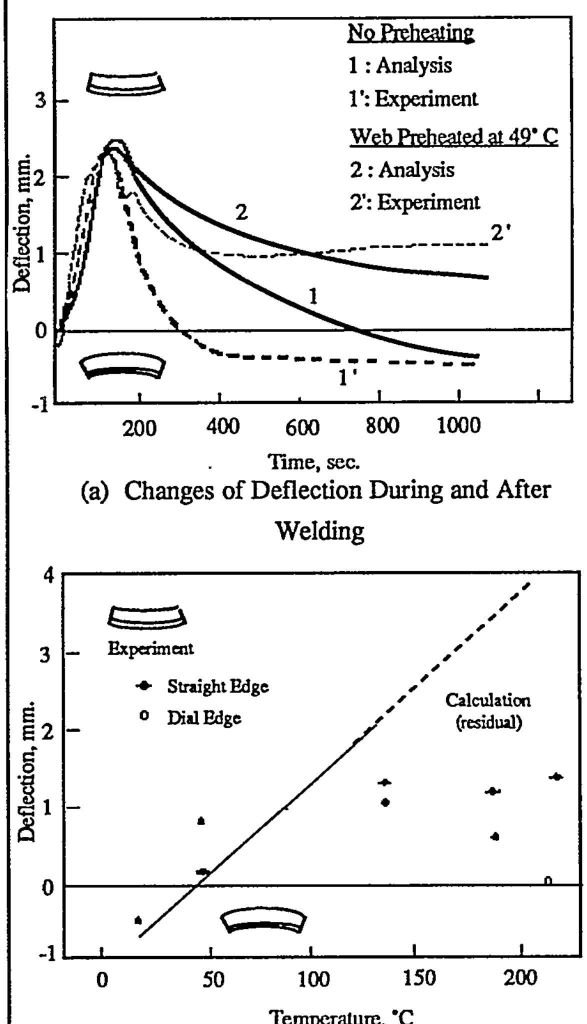
Study 4: Reduction of residual stresses and distortion in weldments in high-strength steels.

Following are brief background discussions of the first two studies performed sometime ago. Then more detailed discussions are given on the last two studies which were performed more recently.

<u>Reduction of Longitudinal Bending Distortion of Built-up Beams</u>

Experimental and analytical studies were performed in the 1970's for reducing longitudinal bending distortion of built-up beams by a technique that is called "differential heating" [l]. The basic idea is to reduce distortion by joining plates with different (properly selected) initial temperatures. Serotta conducted a series of experiments to investigate how differential heating reduces the longitudinal distortion produced during welding fabrication of a T-beam in 5052-H33 aluminum alloy [3]. A web plate, 48"x6"x0.5" (1,220x 152x 12.7 mm), was fillet welded to a flange plate, 48" x 4" x 0.5" (1,220 x 102 x 12.7 mm) by gas metal arc welding. Nishida analyzed the experimental results obtained by Serotta by using the one-dimensional computer program developed at M.I.T. [4]. Figure 2-(a) shows changes of deflections during and after welding fabrication of beams. Analytical results are shown in solid lines, while experimental results are shown in broken lines. The final distortion after the specimen cooled down completely was negative (see the sketch in the lower part of the figure) when initial temperatures of the web and the flange were the same. When the differential heating was used, on the other hand, the final distortion changed to positive (see the sketch in the upper part of the figure).

Figure 2-(b) shows how the preheating temperature of the web affected the final distortion of a built-up beam. The discrepancies between the experimental data and the analytical results were significant when the web was heated to relatively high temperatures. It is believed that the experimental data for high preheating temperatures is not accurate, since the temperature differential is reduced by conduction. The figure shows that the zero distortion can be achieved by heating the web to around 120°F (49°C). When welding is done in more than one pass, the best technique is to produce a slightly negative distortion after the first welding pass by using a higher preheating temperature so that the distortion after completing the final pass will be close to zero.



(a) Changes of Deflection During and After Welding

(b) Calculated Final Center Deflection vs. Preheating Temperature of the web

Figure 2 Reduction of Longitudinal Bending Distortion Due to Welding Fabrication of an I-Beam by Use of the Differential Heating Technique

Reduction of Radial Distortion and Residual Stresses in Girth-Welded Pipes

Studies have been carried out to develop techniques for reducing radial distortion and residual stresses produced by girth-welding of pipes.

In the first study performed by DeBiccari, a turnbuckle was used to provide an additional restraint to a specimen, as shown in the upper right comer of Figure 3 [5]. Forces generated by the turnbuckle were transmitted to the specimen through two semi-circular shoes so that various locations along the girth were subjected to varying degrees of restraint. The turnbuckle was instrumented with strain gages in order to monitor changes of restraining forces during welding. The inner diameter of the pipe was 12 inches (305 mm), and the wall thickness was 5/16 inch (8 mm). Figure 3 shows relationships between the distance (in the direction parallel to the longitudinal axis of the pipe) from the weldedge (the borderline between the weld metal and the base metal) and values of radial contraction measured at four locations along the girth: θ_i = 0, 30, 60, and 90 degrees. Shown in the thick line is the radial contraction obtained on a specimen welded without using the turnbuckle restraining system. The results may be summarized as follows:

(1) Distortion Shape The amount of the radial contraction is the largest near the weld, and it greatly decreases as the longitudinal distance from the weld increases, and

(2) Effectiveness of Additional Restraint The additional restraint provided by the turnbuckle system decreases the radial contraction very effectively. As the angle θ_i increases, the degree of restraint by the shoe decreases; therefore, the radial contraction increases. DeBiccari also found that restraining forces measured by strain gages mounted on the turnbuckle decreased momentarily when the welding arc passed areas where the turnbuckle touched the pipe (θ = 0 and 180 degrees). These reductions of restraining forces are believed to be caused by the expansion of the pipe due to the welding heat. He also found that residual stresses measured on the restrained pipe were generally lower than those obtained on the pipe with no additional restraint.

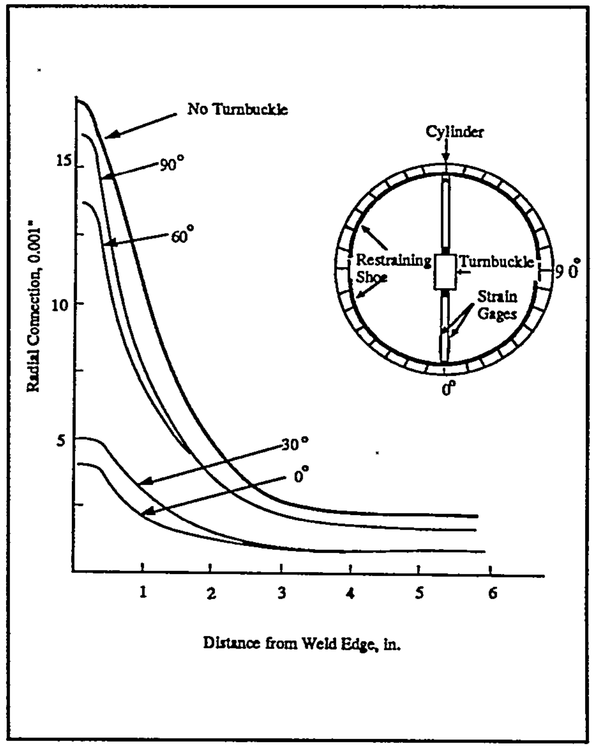


Figure 3 Reduction of Residual Distortion of a Girth Welded Steel Pipe by Application of Internal Pressure Using an Instrumented Turnbuckle System

In the second study performed by Barnes, a restraining system using six hydraulic pistons was constructed and used in order to provide constant amount of restraint to a specimen even while it expands due to the welding heat [6]. The system was designed in such a way that it can be easily assembled in a pipe and easily disassembled after welding is completed.

Reduction of Forces Acting on Tack Welds in a Butt Joint

A research program was performed for the Department of Energy with an objective of minimizing forces acting on tack welds in a butt joint. The program was a part of a larger research program involving both M.I.T. and I.N.E.L. (Idaho National Engineering Laboratory) on automatic control of arc welding.

The uneven temperature distribution caused by the welding arc produces complex transient thermal stresses resulting in mismatch of parts to be joined unless they are securely held together. The joint mismatch that occurs during butt welding, which is shown in Figure 4-(a), can be explained by combining the information given in Figure 1. Suppose that a butt weld is being made with no tack weld, as shown in Figure 4-(a), each of the two parts being joined behaves as shown by Curve OABC in Figure 1. If deformations in regions near the welding arc when they start to cool are near Point A (or somewhere between Points 0 and B), the finishing end of the joint would open. This phenomenon normally occurs during gas metal arc and submerged arc welding of steel plates. On the other hand, when a joint is welded with shielded metal-arc process using covered electrodes, deformations of regions near the weld when they start to cool may be somewhere after passing Point B resulting in closing of the finishing end. This type of distortion is often called "rotational distortion" [1]

A common method of coping with the rotational distortion is to hold the joint with tack welds. This can be done relatively easily in manual welding of small parts. In case of automatic welding, however, dealing with the rotational distortion becomes a complex problem. When welding is performed by a robot, for example, tack welds must be made by a human welder thereby requiring additional manpower and cost. On many occasions, tack welds are performed by an inexperienced person, resulting in less than perfect welds. Also, tack welds, even if they are perfectly made, act as major hazards during the subsequent root pass welding. In fact, it is difficult to completely melt the tack welds during root pass welding causing lack of penetration and other types of defects [7]. In submerged arc welding of a long butt joint of thick plates, forces acting on tack welds are so great that they often break during welding. In fact, Japanese shipbuilders experienced longitudinal cracking of the finishing end when they first introduced one-side submerged arc welding of large ship plates [8].

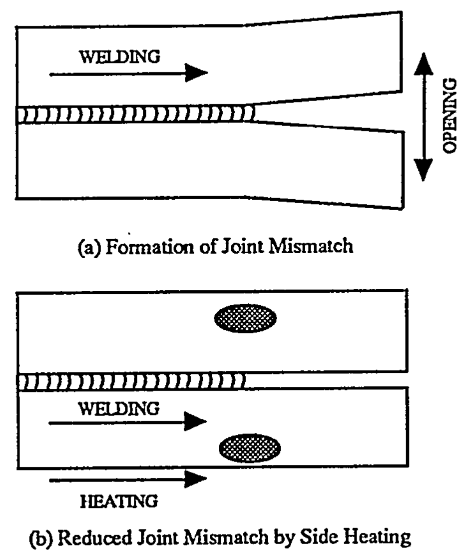


Figure 4 Mechanisms of Formation of Joint Mismatch by Side Heating

Chang, Park, and Miyachi performed experimental and analytical studies for reducing forces acting on tack welds during butt welding [9-11]. The basic idea used by Chang was to reduce the joint mismatch or the rotational distortion by side heating, as schematically shown in Figure 4-(b). By performing side heating while welding is performed, it may be possible to produce additional thermal stresses that can counteract those produced by welding. It is important, however, that the additional heating not produce additional residual stresses.

Figure 5-(a) shows the experimental set up used by Chang [9]. Instead of using tack welds for holding plates to be joined, a semi-circular ring was attached to each end of the joint. The rings were instrumented with strain gages in order to measure changes of deformation at these ends. Although the rings were welded to the plates in experiments, these rings can be designed in such a way that they can be clamped to plates to be welded in actual fabrication. Efforts were made to reduce the opening of the finishing end by altering the thermal pattern in the weldment during welding. Two oxygen torches were mounted on a frame with a welding head so that the side heating system could be moved along with the welding arc. The position of the heating system relative to the welding head could be adjusted in three directions, x, y, and z, as shown in Figure 5(a), in order to control the side heating procedure. The system was used mainly for controlling the joint mismatch or the rotational distortion in a steel weldment.

<u>Results on Steel Weldments.</u> Figure 5 (b) shows typical results obtained on a low-carbon steel weldment, 36 inches (914 mm) long, 24 inches (610 mm) wide, and 0.5 inch (12.7 mm) thick, with no side heating. Data on the left figure show results for a weld without side heating, while data on the right figure show results for a weld with side heating.

Very soon after welding commenced, the starting end began to shrink. Note that when closing of a joint occurs, strains measured on gages attached on the outer surface of the ring would be tensile. The side heating caused little effect on forces acting on the ring attached to the starting end. On the other hand, forces acting on the finishing end were greatly affected by the side heating. On the specimen without side heating, the finishing end first opened a considerable amount as welding

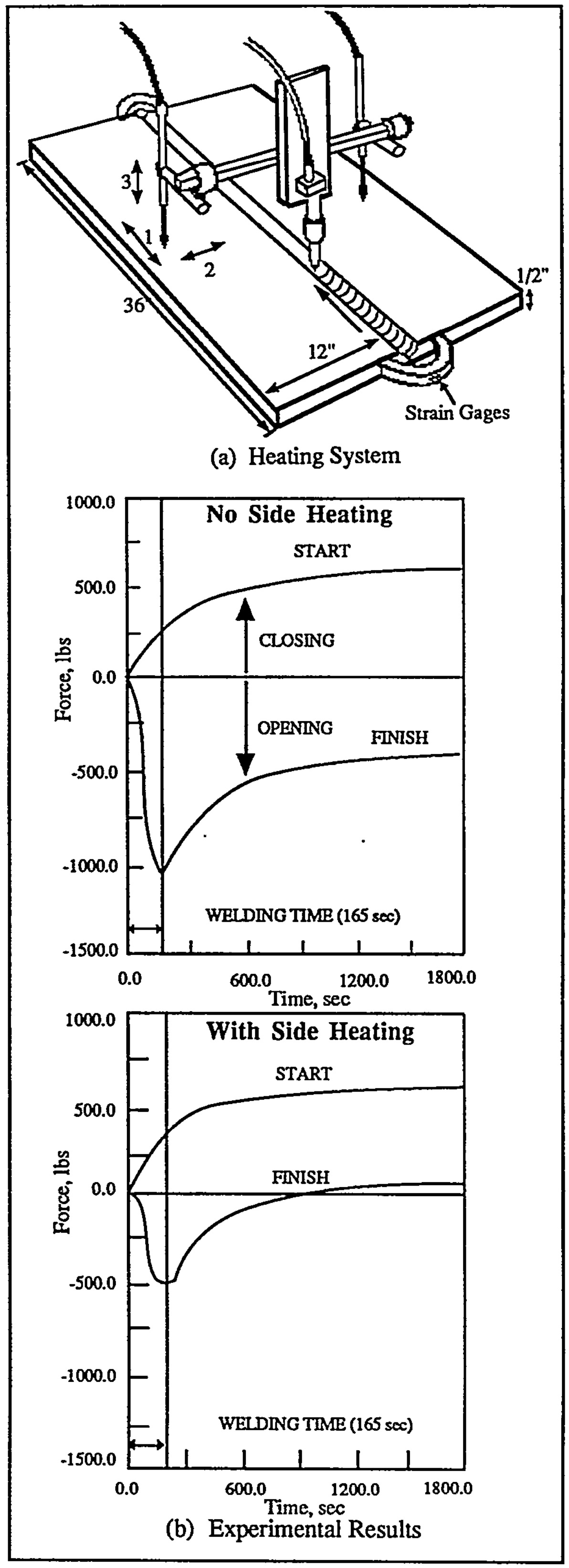


Figure 5 Reduction of Forces Acting on the Rings Attached to Starting and Finishing Ends of a Butt Weld

progressed, and it began to shrink after welding was completed. Almost all of the difference between the movement of the starting end and that of the finishing end was produced during welding. Welding was completed in 165 seconds, but it took approximately 1,800 seconds (30 minutes) before forces acting on the rings were fully developed.

The right graph of Figure 5-(b) shows results obtained on a steel weldment with side heating. It is clear that the amount of joint opening decreased significantly by use of the side heating. Results illustrate that the deformation at the starting endis little affected by the side heating. This indicates that the measurement at the starting end can be used as a control. In other words, the joint mismatch can be minimized as long as the strain measurements on the finishing end are similar to those obtained on the starting end.

An analytical study was made using a one-dimensional program to determine optimum conditions for side heating. It was found that the most effective method was to heat wide regions away from the weld to moderate temperatures (around200°For93^{0}C) to accomplish the following:

(a) The side heating should produce thermal stresses large enough to counteract those produced by welding,
(b) The side heating should not produce additional residual stresses.

In order to develop a strategy for the most effectively control the joint mismatch, a series of experiments as performed to study effects of torch movements in the x-, y-, and z-directions. It was found that forces acting on the ring (a simulated tack weld) at the finishing end can be significantly reduced by a proper side heating. For example, the maximum opening force observed on a ring attached to the finishing end was reduced from 1,125 pounds (506 kg) without side heating (welding only) to only 105 pounds (47 kg) with side heating.

Resultson Aluminum Welds. A limited amount of work was performed on aluminum welds by Park [10]. First, experiments were performed to study effects of side heating on forces acting on rings attached to both ends of aluminum butt welds 36” x 24” x 0.5” in size. Results were disappointing. For example, the maximum opening force observed on a ring attached to the finishing end increased from 300 pounds (135 kg) on a weld without side heating to 700 pounds (315 kg) on a weld with side heating. This is probably due to combined effects of the following:

(a) Compared with steel, aluminum has a large heat conductivity (approximately 5 times that of steel). Therefore, the heat spreads much more rapidly in aluminum than in steel. In order to produce thermal stresses large enough to counteract those produced by welding using side heating there must be uneven temperatures caused by both the welding arc and the side heating. In an aluminum weld, the heat spreads so rapidly that temperature distributions caused by the welding and the side heating cannot be well separated.
(b) Compared with steel, aluminum has a larger coefficient of linear thermal expansion (approximately 3.5 times of that of steel). Therefore, the best method for reducing distortion in an aluminum weld is to lower temperatures, not to increase them by additional heating.

It was decided to study effects of forced cooling on the joint mismatch during welding of an aluminum butt joint. Since it was difficult to have a heat sink that could travel with the welding arc, it was decided to cool the joint before welding and to keep the cooling system operating during the entire welding period. Crushed dry ice particles were used to cool regions near the weld. Then the maximum force observed on a ring attached to the finishing end decreased from 300 pounds (135kg) without cooling to mere 30 pounds (13.5 kg) with cooling. The results show that the key for reducing the joint mismatch (and perhaps residual stresses also) in an aluminum weld is to keep the temperatures in the weldment as low as possible.

Reduction of Residual Stresses and Distortion in Weldments in High-Strength Steels

Various types of high-strength steels are increasingly used for welded marine structures to reducing structural weight and improve service performances. For example, the U. S. Navy, having used HY-80 and HY-100 steels for many years for submarine hulls is considering using HY-130 steel for pressure hulls of future submarines. HY-80, HY-100, and HY-130 steels are quenched-and-tempered steels with the minimum specified yield strengths of 80,100, and 130 ksi (552,689, and 896 MPa), respectively. Since yield stresses of these steels are high, there is always a possibility of producing very high residual stresses in some regions near welds, including at the end of repair welds and in regions near structural discontinuities (such as the end of a fillet weld connecting a flat plate and a stiffener). High transient thermal stresses during welding and residual stresses may cause some of the following problems:

(a) Since steels with higher strengths tend to become more sensitive to weld cracking, higher transient thermal stresses can promote weld cracking.
(b) Since steels with higher strengths tend to become more sensitive to environmental effects such as stress corrosion cracking and hydrogen embrittlement, high tensile residual stresses may promote environment assisted cracks during service.
(c) Since design stresses are higher for structures of higher strength steels, these structures tend to have increased tendencies of fatigue failures. Higher tensile residual stresses may promote these fatigue fractures.

Efforts have been made to study methods of reducing residual stresses and distortion in high-strength steel weldments. A one-year research program was conducted in which Bass and Vitooraporn performed experimental and analytical studies on residual stresses and distortion in bead-on-edge welds in three types of steels including low-carbon steel (ABS Grade B), HY-100, and HY-130 steels [12,13]. HY-100 and HY-130 steels were made available through the U.S. Navy.

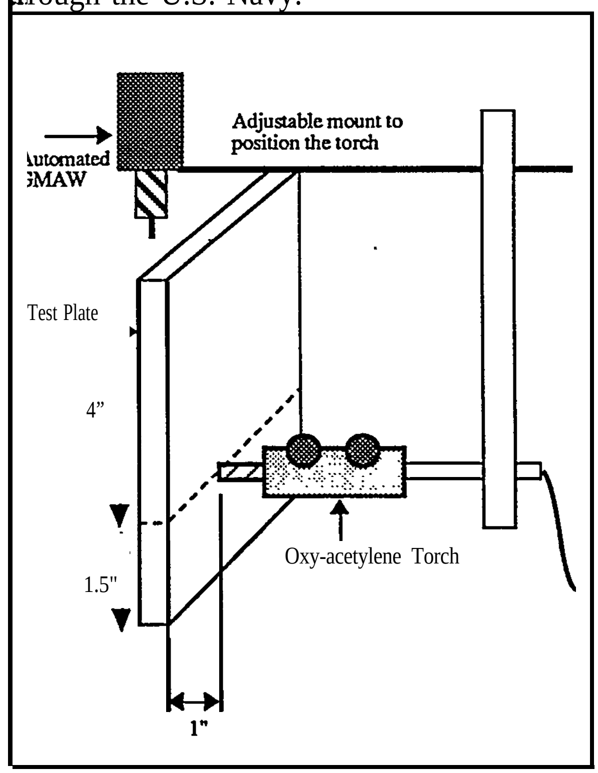


Figure 6 Experimental Set-up Used by Bass and Vitooraporn

Figure 6 shows the experimental set-up. Test specimens were 5.5 inches (140 mm) wide, 18 inches (457 mm) long, and 0.5 inch (12.7 mm) thick. Welding bead was laid using gas metal arc process along the upper longitudinal edge of a specimen placed in the vertical position. An E7OS filler wire 0.045 inch (1.1 mm) in diameter was used for all experiments. Typical welding conditions were as follows:

Polarity: direct current reverse polarity
Shielding gas: 98% argon, and 2% oxygen
Welding current: 230 Amperes
Arc voltage: 25 Volts
Arc travel speed: 0.300 in/set (7.6 mm/sec).

Some specimens were welded without side heating, while others were welded with side heating using an oxyacetylene torch positioned 4 inches (102 mm) from the upper edge of the specimen. The side heating conditions were selected in order to produce the maximum temperatures of approximately 2OO°F (93°C) in the specimen.

During welding, measurements were made of: (1) strains using electric resistance strain gages, (2) temperatures using thermocouples, and (3) deformation using dial gages. After welding was completed, residual stresses were determined by a stress relaxation technique in which a narrow strip containing strain gages was removed from the specimen. Experimental results were analyzed using (a) analytical modeling techniques and (b) numerical techniques using a finite element method.

Experimental results are summarized in Figures 7 through 9. Figure 7 shows results obtained on specimens in low-carbon steel. Figure 7-(a) shows distortions measured by a dial indicator placed at the center of the plate during welding and after welding of specimens. Figure 7-(b) shows relationships between the lateral distance from the weld and longitudinal residual stresses. Figures 8 and 9 show similar data obtained on specimens in HY-100 steel and HY-130 steel, respectively.

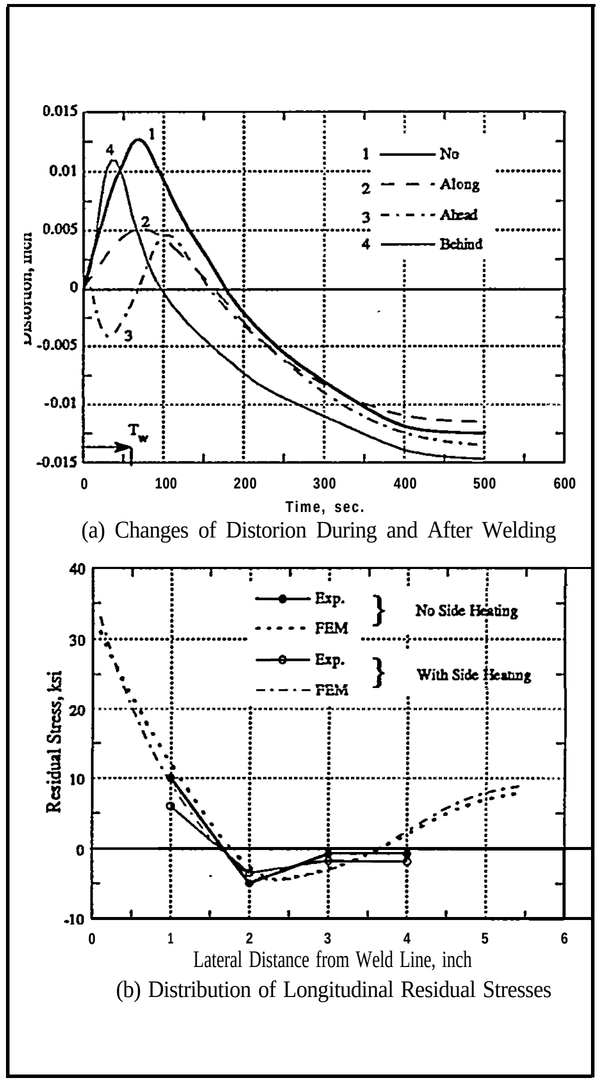


Figure 7 Reduction of Distortion and Residual Stresses by Side Heating in Low-Carbon Steel Specimens

The results may be summarized as follows:

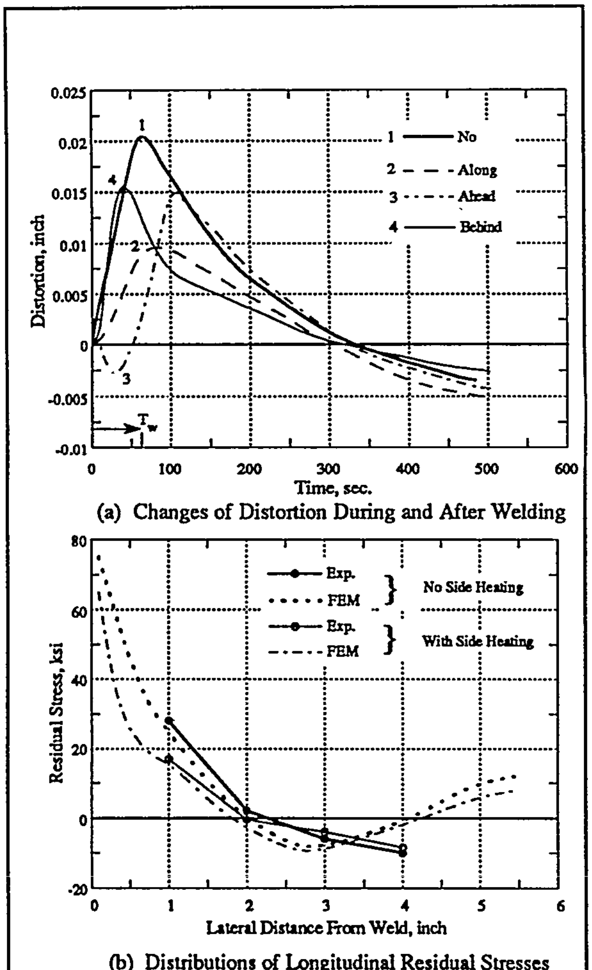
(a) Distortion Changes. Figures 7-(a), 8-(a), and 9-(a) show changes of deformation during and after welding measured at the mid-length of the specimen (9 inches or 229 mm from the edge) of specimens in low-carbon steel, HY-100 steel, and HY-130 steel, respectively. Each of the figures contain data obtained under the following four conditions:

Condition 1: No side heating;
Condition 2: The side heating torch positioned along the

welding head;

Condition 3: The side heating torch 9 inches (229 mm) ahead of the welding head; and

Condition 4: The side heating torch 9 inches behind the welding head.

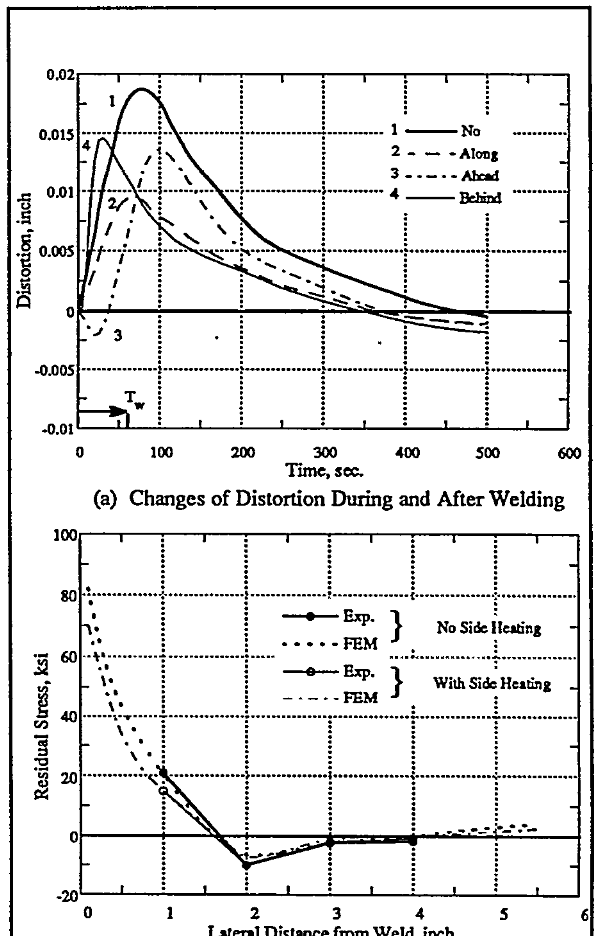


(a) Changes of Distortion During and After Welding

(b) Distributions of Longitudinal Residual Stresses

Figure 8 Reduction of Distortion and Residual Stresses by Side Heating in HY-100 Steel Specimens

The side heating behind the welding arc (Condition 4) was found to be not as effective in reducing distortion. In other words, it was too late to try to reduce distortion after welding. The side heating ahead of the arc (Condition 3) caused rather complex changes of distortion. The plate first moved by the heating torch, and then it moved again by the welding torch. Researchers have come to a conclusion that the side heating ahead of the arc is not a recommended method since it produces distortion changes that are too complex. Researchers favor the effects created by the side heating along the arc (Condition 2), since changes of distortion during the entire period of welding and subsequent cooling were kept rather small. It has been concluded that the side heating along the welding arc is a good method for controlling distortion.



(a) Changes of Distortion During and After Welding

(b) Distributions of Longitudinal Residual Stresses

Figure 9 Reduction of Distortion and Residual Stresses by Side Heating in HY-130 Steel Specimens

(b) Residual Stresses. Figures 7-(b), 8-(b), and 9-(b) show lateral distributions of longitudinal residual stresses, ox, along the middle section of the specimen in low-carbon steel, HY-100 steel, and HY-130 steel, respectively. Shown in each figure are four sets of curves as follows:

(a) Results on a specimen without side heating:
- (a-l) Experimental data; and
- (a-2) Calculated results using the finite element method

(b) Results on a specimen with side heating:
- (b-l) Experimental data; and
- (b-2) Calculated results using the finite element method.

The results show that residual stresses were reduced to some extent by the side heating.

Conclusions on the Effectiveness of the Side Heating Technique. On the basis of the results obtained in this study and the previous study on forces acting on tack welds, the following comments as to the effectiveness of side heating as a method of reducing residual stresses and distortion can be made:

(1) Forces Acting on Tack Welds. The side heating technique is very effective in reducing joint mismatch and forces acting on tack welds in a steel weldment.

(2) Distortion. Distortion can be reduced significantly by side heating, especially by side heating along the welding arc.

(3) Residual Stresses. The side heating can accomplish reduction of residual stresses to a certain extent; however, the extent of reduction of residual stresses is less than that of reduction of distortion. This is understandable, because the side heating can significantly affect the movement of a weldment as a whole. But the effectiveness of side heating for reducing residual stresses in regions near the weld are less, because residual stresses are more affected by temperature distributions close to the weld. More drastic reduction of residual stresses may be achieved by locally heating the regions near the weld to moderate temperatures after welding is completed. In fact, Greene and Holzbaur found in the 1940's that residual stresses could be reduced significantly by a technique called "low temperature stress relieving" [14, 15]. This system employs the oxyacetylene flame to heat simultaneously two strips, one on each side of a weld joint, to 500°F (260°C), in such a way their expansion stretches the weld plastically, reduces the peak residual stresses, and alters the stress gradient [15]. On the basis of the new study, a significant reduction of peak residual stresses in a weldment in a high-strength steel may be accomplished by heating a wide region to only moderate temperatures around 200°F (93°C). Further research is needed for evaluating the usefulness of the low-temperature stress relieving on high-strength steel weldments for critical structures.

(4) Aluminum Welds. The side heating technique is not recommended on an aluminum structure. In fact, the basic principle for minimizing residual stresses and distortion in an aluminum weld is to minimize the heating of the weldment.

OTHER RESEARCH ACTIVITIES

Presented below are brief summaries of several other projects related to residual stresses and distortion in weldments.

Forming of Steel Plates by Line Heating with a High-Power Laser Beam

A technique involving heating with an oxyacetylene torch has been widely used for straightening distorted plates as well as forming plates into various shapes. For example, Japanese shipbuilding companies extensively used line heating techniques for bending steel plates [1]. A research project was performed to investigate whether steel plates can be formed by use of the line heating technique with a high-power laser beam (approximately 5-10 kilowatts in power) instead of an oxyacetylene torch. The program was performed for the U.S. Navy through Todd Pacific Shipyards Corporation [16-18]. Tests were performed on low-carbon steel plates l/4 through 1 inch (6.4 through 25.4 mm) thick. Some tests also were made on plates in HY-80 steel and other low-alloy high-strength steels.

Results obtained in the program may be summarized as follows.

(1) The laser line heating is a very effective method of forming steel plates, especially with a thickness of around l/4 to 1/2inch (6.4 to 12.7 mm). The practical maximum thickness for laser line heating appears to be around 1 inch (25.4 mm), and the practical maximum heat input is approximately 65 KJ/in (165 KJ/cm).

(2) Material degradations were observed on specimens subjected to laser heating using high heat input (54 KJ/in or 137 KJ/cm). However, the material degradation could be eliminated, practically speaking, by applying multipass heating techniques using a small heat input (3 passes of 18KJ/in per pass).

It should be noted that all of the novel techniques for measuring out-of-plane distortion described earlier in this paper were successfully used in this research program.

<u>Intelligent System for Flame Straightening of Panel Structures</u>

Distortions which occur during the assembly of steel panel plates can be removed by flame straightening - a technique that has been used for a number of years in the shipbuilding industry. Many years of experience are usually needed to acquire the skill required to correctly perform flame straightening of complex structures such as ships. The problem that the industry faces now is that many of the skilled human experts have retired or are retiring, and it is extremely difficult to secure younger people who are willing to spend many years to acquire these needed skill. One way to improve the situation is to develop a robot capable of not necessarily replacing a human worker but helping a human worker. A study was performed with the ultimate objective of developing an intelligent machine capable of performing flame straightening on a deck of a ship super structure [19]. This study thus far includes (a) development of algorithms for determining heating conditions and (b) development of sensors needed for in-process sensing and control of robot movements.

<u>Development of a Knowledge-Based System for Minimizing Out-of-Plane Distortion of Welded Panel Structures</u>

Weld distortions in a complex structures are affected by many parameters. Some of the parameters include:

(a) Structural geometry
- Plate thickness
- Frame spacing

(b) Welding processes
- Shielded metal arc
- Gas metal arc
- Submerged arc

(c) Material type
- Low-carbon steel
- High-strength steel
- Aluminum alloys

(d) Joint type:
- Butt joint
- Fillet joint

(e) Distortion type

Distortion due to angular change
Buckling distortion
Longitudinal shrinkage
Transverse shrinkage
Longitudinal bending distortion.

For minimizing distortion of welded structures, it is very important to select proper combinations of these parameters. Regis has performed a preliminary study for developing a computer-aided system for selecting proper combinations of these parameters [20]. His work covers mainly out-of-plane distortion of panel structures composed of a flat plate with longitudinal and transverse stiffeners fillet welded to the plate.

CONCLUSION

A weldment undergoes complex changes in thermal stresses during welding, and in residual stresses and distortion after welding is completed. It is important to understand the mechanisms of formation of these stresses and strains in order to develop rational methods for controlling and reducing these stresses and distortion. The most effective method for achieving the objective of controlling and reducing these stresses and distortion is to apply proper controls during welding, while non-elastic strains that cause these stresses and strains are being formed. The concept of providing additional real-time control is not realistic in fabrication using manual welding, but it should be possible in fabrication using automatic welding.

The first part of this paper covers summaries of experimental and analytical studies for controlling and reducing residual stresses and distortion in several types of fundamental welded joints. The author hopes that some of the basic principles developed in these studies are applicable to actual constructions of welded marine structures. The second part provides a brief summary of other activities related to residual stresses and distortion. The author also hopes that a collection of these efforts will provide engineers and managers in the shipbuilding industry scientific basis for design and fabrication of more reliable welded marine structures with reduced costs.

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